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Field Verification of Load Transfer Mechanics of Fully Grouted Roof Bolts

By S. P. Signer

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BUREAU OF MINES

UNITED STATES DEPARTMENT OF THE INTERIOR

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ILLUSTRATIONS

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	min	minute
in	inch	pct	percent
lbf	pound (force)	V	volt

FIELD VERIFICATION OF LOAD-TRANSFER MECHANICS OF FULLY GROUTED ROOF BOLTS

By S. P. Signer[1]

ABSTRACT

The Bureau of Mines conducted a series of field tests to improve the understanding of the support interaction mechanics between fully grouted bolts and coal mine roofs and to help lay the foundation for improved design and evaluation techniques. Strain gauges were installed on 14 fully grouted bolts placed in shale roof rock at four mines in Colorado, Illinois, and Pennsylvania to determine how load was transferred between the bolts and the rock. The results of field tests on elastic bolt behavior compared well with previous laboratory work and numerical models. The field tests showed that the anchorage length of grouted bolts installed in shale was slightly longer than the anchorage length determined in laboratory tests conducted in concrete blocks. The field results produced more variability because of geological variations. Tests run past the yield point of the steel bolt indicate that the yield zone varies significantly and translates down the length of the bolt anywhere from 4 to 22 in.

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INTRODUCTION

To prevent structural failure of a mine roof, fully grouted bolts are used in situations where mechanically anchored bolts are inadequate for providing support. Fully grouted bolts have a greater area of contact with the rock, which allows for development of higher anchorage capacities. This is one reason why the use of grouted bolts has been increasing since the mid-1970's.

Even so, roof falls have occurred in areas supported by fully grouted bolts. Generally, bolting patterns for required roof control plans are based on past practices, which, in turn, have been derived from trial and error. As a result, overdesign may result in unnecessary cost or underdesign may allow roof falls.

To ensure the safe and efficient use of fully grouted bolts, it is necessary to develop guidelines for selection of bolt type, diameter, spacing, and length, given specific geologic conditions. Numerical modeling is one approach to solving this design problem. A numerical model can be used to aid in the determination of effective bolt type, diameter, spacing, and length by considering factors such as geology, discontinuities, time effects, mine geometries, and in situ field stresses. Types of numerical models include finite element, boundary element, and distinct element. Development of any of these models necessitates adequate definition of the mechanics of interaction between the bolt and the mine roof.

The behavior of ground support systems that incorporate grouted roof bolts has been studied by many people. Several theoretical approaches for evaluating and designing the appropriate length and spacing of grouted bolts have been formulated (*1-11*),[2] numerical models of grouted bolt systems have been developed (*12-13*), and empirical approaches based on rock mass identification and classification have been proposed (*14*). Laboratory models have been created to study the effects of shear resistance of grouted bolts and to determine how shear resistance produces beam building in mine roofs (*15-17*). Bolts have been instrumented with strain gauges and studied both in the laboratory and in situ (*18-25*). However, the mechanics of interaction among parts of the grouted bolt system (bolt, grout, and mine rock) have not been well defined or verified.

The Bureau of Mines has undertaken a study to improve the understanding of how fully grouted bolts interact with the mine rock to provide support. Work has begun at Bureau research centers to provide a fundamental knowledge of how to design, install, and evaluate fully grouted roof bolt systems properly. The objective of the study at the Spokane Research Center is to increase the understanding of the load-transfer mechanics of fully grouted bolts through comparing numerical models to laboratory and field test results. This will lead to development of methods for more accurate designing of roof support using fully grouted bolts. The benefits to be gained are substantial. Proper design and evaluation procedures could decrease the number of roof falls, which would increase both safety and productivity.

The approach taken in this study was to control as many variables as possible to establish a baseline of information. Each variable was then studied to determine its effect on the interaction mechanics.

For this reason, work began with investigations of the axial elastic behavior of grouted bolts installed in concrete blocks. The compressive strength of these blocks was comparable with that of a typical shale roof. Over 50 pull tests were performed in the laboratory on grouted bolts instrumented with strain gauges to measure load changes along the length of the bolt. Applied loads were restricted to the elastic range of the steel. Variations were made in hole size, bolt length, grout type, and grout strength. Results from an axisymmetric finite-element numerical model was compared with these test results and is detailed in reference 1.

To determine if the results from the laboratory tests could be applied to conditions encountered in mine rock, similar tests were performed at four different coal mines in Colorado, Illinois, and Pennsylvania. The comparisons between the laboratory tests and field tests are detailed in this report.

ACKNOWLEDGMENTS

The author would like to thank mine personnel at the Eagle Mine, Craig, CO; the Wabash Mine, Keensburg, IL; the Galatia Mine, Harrisburg, IL; and the Warwick Mine, Greensboro, PA, for their assistance and cooperation during installation of the instruments.

[2]Italic numbers in parentheses refer to items in the list of references preceding the appendix at the end of this report.

LOAD TRANSFER MECHANICS

The redistribution of forces along a bolt is the result of movement in the roof strata. This movement may be vertical (strata separation) or horizontal (strata slippage). One mechanism that retards strata slippage is a doweling effect created when the grout and bolt completely fill the hole. Strata separation is resisted by the axial strength of the roof bolt. This study will examine only the axial response of the bolt system.

Load is transferred between the bolt and the rock by shear resistance in the grout. This resistance could be the result of adhesion and/or mechanical interlocking. Adhesion is an actual bonding or gluing among the grout, the steel, and the rock; and mechanical interlock is a keying effect created when grout fills irregularities between the bolt and the rock. Adhesion is considered by some researchers to be the primary means of shear resistance in a grouted bolt system. However, test bolts were examined and showed no adhesion between the grout-bolt or grout-rock interfaces.

Mechanical interlock will transfer load between the steel bolt, the grout, and the rock through contact surfaces. Bolt hole walls have voids and irregularities resulting from both the drilling process and variations in roof lithology. Steel bolts are rolled with ribs to provide an irregular surface. Grout fills these irregularities and voids if the bolt is properly installed. When load develops in the bolt, stress concentrations occur between the irregularities in the bolt hole walls and the rolled ribs of the steel. This localized stress concentration could exceed the strength of the grout and/or rock, resulting in localized crushing that allows additional deflection in the steel. The length required for mechanical interlock to transfer all the load from the bolt to the rock is the anchorage length.

The anchorage length depends on the material properties of the steel, the grout, and the rock; the quality of the installation; the smoothness of the drill hole; and possibly other factors such as grout annulus. Weaker grout and/or rock may require longer anchorage lengths because of reduced shear strength. Proper installation of the bolt system is critical to its performance. If the grout is inadequately mixed, is overspun, or is glove fingered, then the capacity of the grout to provide mechanical interlock is severely impaired. Glove fingering occurs when parts of the plastic wrapper of the resin cartridge is not shredded during installation.

Various types of axial failure can occur when using grouted bolts. Failure can take place in the bolt, the grout, the rock, or at the bolt-grout or grout-rock interfaces. The type of axial failure depends on the characteristics of the system and the material properties of individual elements.

If the bolt has sufficient length to transfer all the bolt load to the rock, then the bolt will fail if the ultimate strength of the bolt is less than what is required to support the rock load. Adjustments in the design of bolt spacing, length, diameter, and strength must be made so that the capacity of the bolting system is sufficient.

The steel is stronger and more ductile than the grout and the rock. For this reason, localized failure will occur in the grout and/or the rock after loading has exceeded the tensile strength. After the steel has exceeded yield, then this localized failure in the grout and rock will enable the steel yield to progress along the bolt length.

If the bolt has insufficient length to transfer the bolt load to the rock, then localized failure will occur at the weakest area and will progress until either equilibrium is established or failure occurs, so that the bolt no longer provides support. Prevention of this type of failure requires adjustments in the design of the bolt length and possibly the bolt spacing.

TEST PROCEDURES

BOLT LOADING

Pull tests are routinely performed on roof bolts in underground mines to evaluate anchorage capacity. This study used a pull-test procedure to investigate the transfer of applied load from the bolthead to the rock. The rate at which load was transferred out of the bolt and into the rock was measured with instrumented roof bolts.

Figure 1 shows the pull-test gear arrangement. The pull-test gear consists of a pull collar placed at the bolthead. Over this collar a crow's foot is attached, which, in turn, is connected to a threaded rod. Force is applied to the head of the bolt by a hydraulic ram that is activated by a hand pump. The applied force is monitored with a pressure gauge and a pressure transducer.

When load is applied to the system, the bolthead will deflect. These deflections are measured at the end of the pull gear by a dial gauge, which is accurate to within 0.001 in. For the linear experiments, force was applied to the bolthead in increments of 1,830 lbf, beginning at 920 lbf and ending at 12,800 lbf, which is approximately 80 pct of the yield of the bolt. The applied force at the bolthead was maintained at each level for 5 min so the system could stabilize before readings were taken. Three loading cycles were conducted for each test. The data were reduced using a linear relationship between voltage change and load change and were plotted to determine the force in the bolt at six gauged stations, as explained in the section on instrumentation.

The applied load for the tests conducted past the yield point of the steel was increased incrementally until the strain gauges failed.

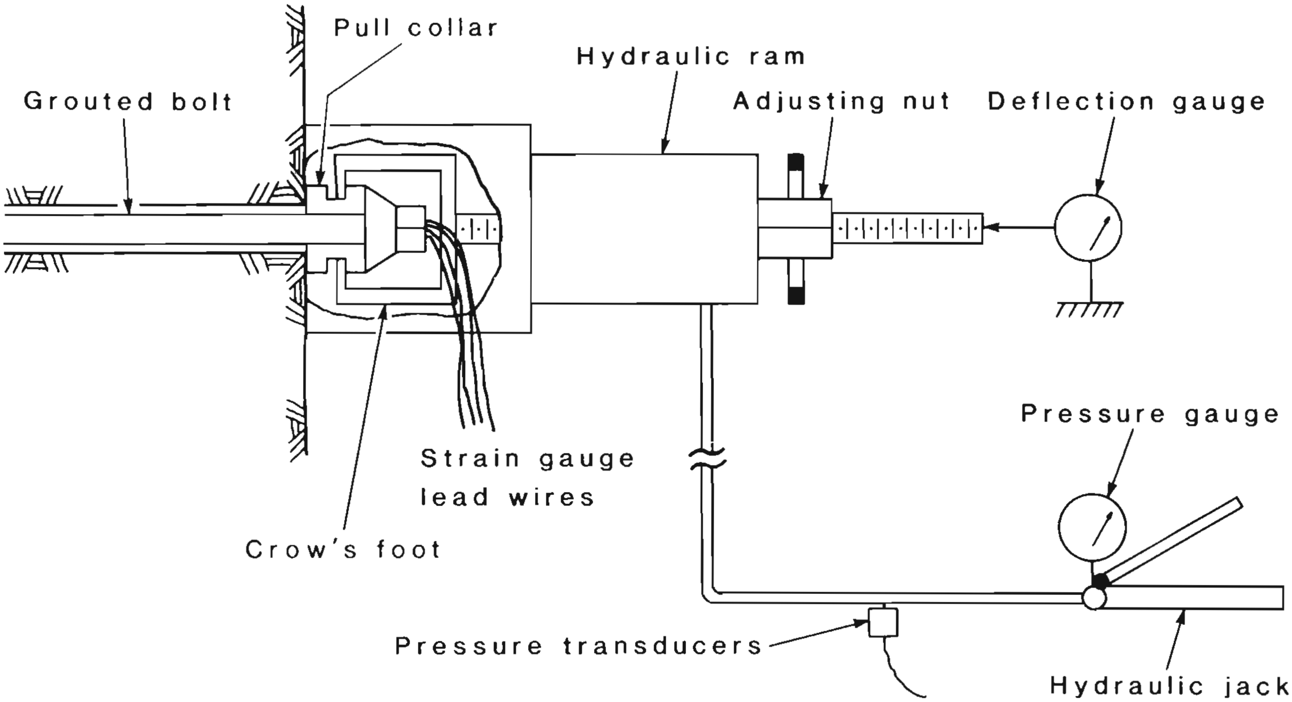

Figure 1.–Pull-test gear arrangement.

INSTRUMENTATION

The bolts used in this study were slotted with two continuous cuts along the length of the bolt, and strain gauges were attached (fig. 2). Each slot was 0.25 in wide and 0.125 in deep. This configuration allowed up to six gauges to be placed along one side of the bolt. The gauges were positioned in pairs on each side of the bolt to account for any bending effects and to provide redundancy. All bolts were grade 40, No. 6 steel bars with forged heads, and all were from the same lot. (However, tests conducted on the bolts indicated a yield point comparable with grade 50 steel.)

Typically, instrumented bolts measure strain, and the load is then calculated using the modulus of elasticity and the area of the bolt. This method presents problems because the area of the bolt cross section is not well defined, and gauge alignment is critical in obtaining accurate results. In this experiment, strain gauges were installed on the bolts and, using statistical methods, were calibrated in a uniaxial tension machine to correlate voltage change directly with load. This technique eliminated problems of area reduction, gauge location, and localized inconsistencies in the bolt and produced excellent test results having good repeatability. The procedure is presented in more detail in the appendix.

TEST SITES

Tests were performed at four different coal mines, one in Colorado, two in Illinois, and one in Pennsylvania; all four mines had shale roofs in the test areas. The bolts were installed off pattern in recently cut roof.

At the Colorado test site (mine 1), a Micromeasurement P-3500 Strain Indicator[4] was used to measure strain changes. The strain readings were converted to load by using calibration factors obtained from prior laboratory axial tension tests. At the next three test sites in Illinois and Pennsylvania (mines 2, 3, and 4), a portable data acquisition system collected data from the strain gauges and pressure transducer and stored the raw voltage readings for later computer reduction. The system provided 5-V excitation to a full bridge configuration. Details of this system are also included in the appendix.

Bolt holes at mine 1 were drilled using water, while bolt holes at the other three mines were drilled with a dry vacuum system. At mine 2, the vacuum system on the drilling machine did not work. Therefore, the holes had to be brushed to remove accumulated dust. It was found that hole diameters at this test site were larger than normal, which caused two bolts to have a partial grout column and required using a thin wire to measure them. Test results from these two bolts were not averaged with the other results. Five bolts were tested at mine 1 and three bolts were tested at each of the other mines.

[4]Reference to specific products does not imply endorsement by the Bureau of Mines.

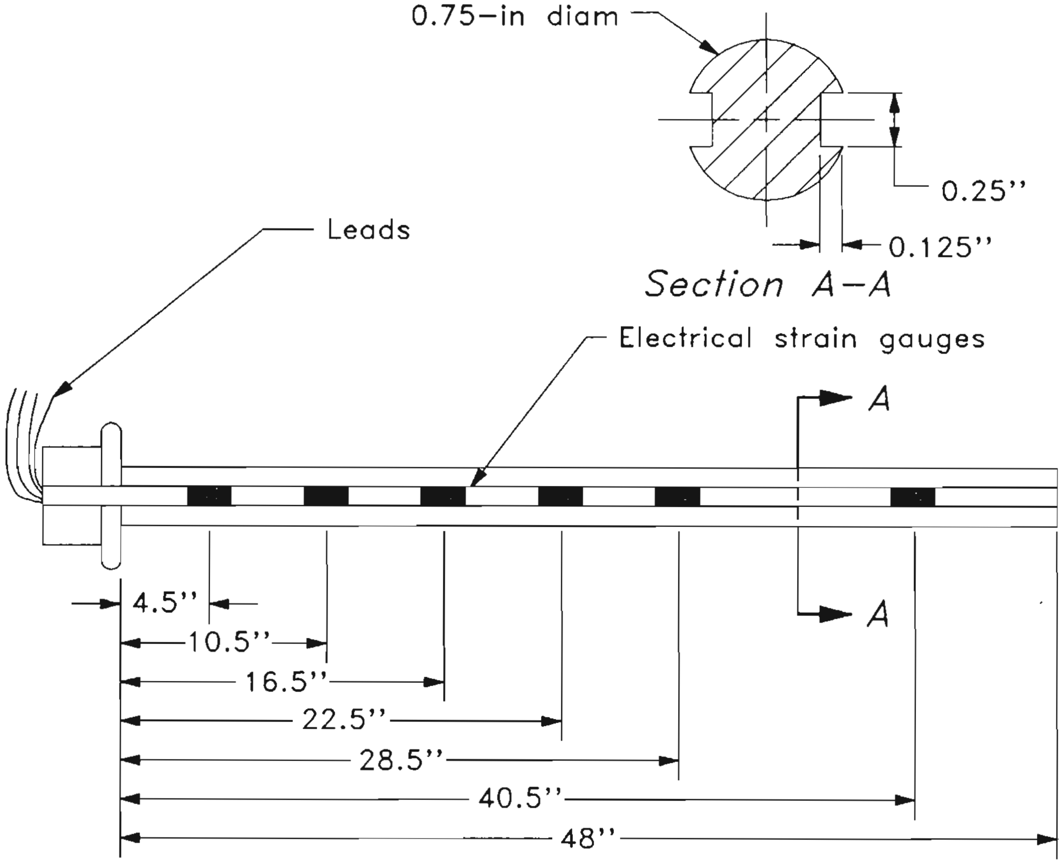

Figure 2.–Gauge locations on instrumented bolts. Pull collars reduce distance from roofline by 1 in.

TEST RESULTS

Readings from the bolts installed at mines 2, 3, and 4 were averaged and the results are shown in figure 3. Each curve represents load decay along the bolt length and was established from readings of the load on the bolts and strain gauges. The length necessary to transfer all the load from the bolt to the rock varied slightly after 4,000 lbf of load had been applied. The slope of each curve is an indication of the stiffness of the system. Increasing the load resulted in higher stiffnesses, indicating that mechanical interlock among the bolt, the grout, and the rock was the primary mechanism for transference of load. If adhesion were the primary mechanism of load transfer, then the stiffness would be the same for all elastic loads and the anchorage length would significantly increase as a function of applied load.

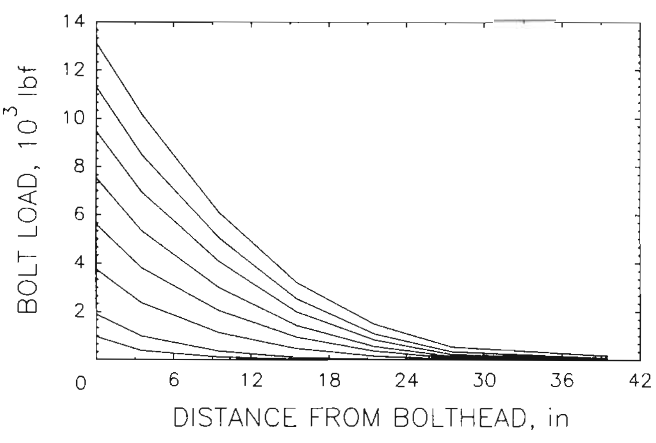

Figure 3.–Average field test results.

ELASTIC TESTS

Elastic tests in which grout type, hole size, and bolt length were varied were conducted in the laboratory on over 50 bolts. Results indicated that 22 in of bolt length was required to transfer 90 pct of the load from the bolt to the rock. Polyester resin and gypsum grout were used with a 3/4-in bolt and installed in 1-in holes. Because adequate mixing of gypsum grout did not pose a problem, this grout was used to test 3/4-in bolts in 1-3/8-in holes.

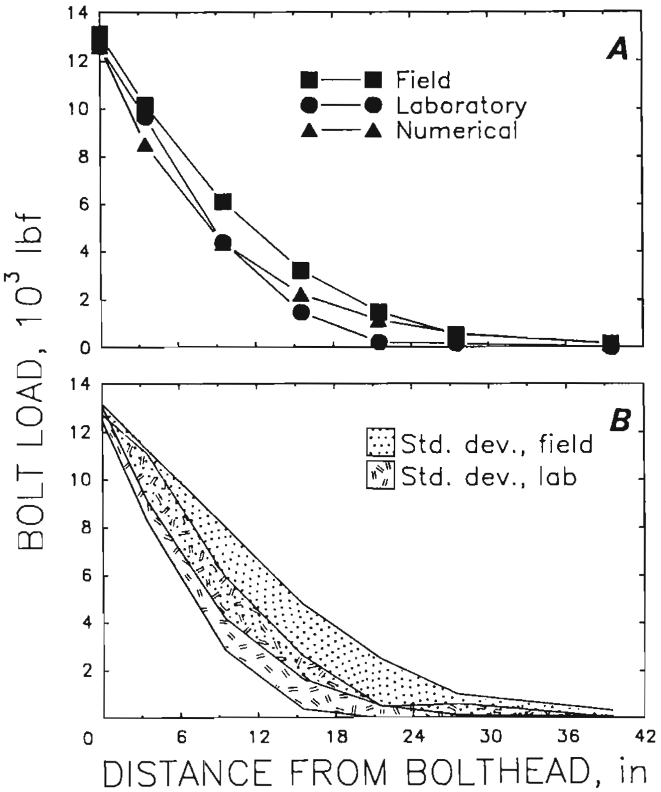

Figure 4.-Comparison of results. *A*, Field tests, laboratory tests, and numerical model; *B*, standard deviations, field tests versus laboratory tests.

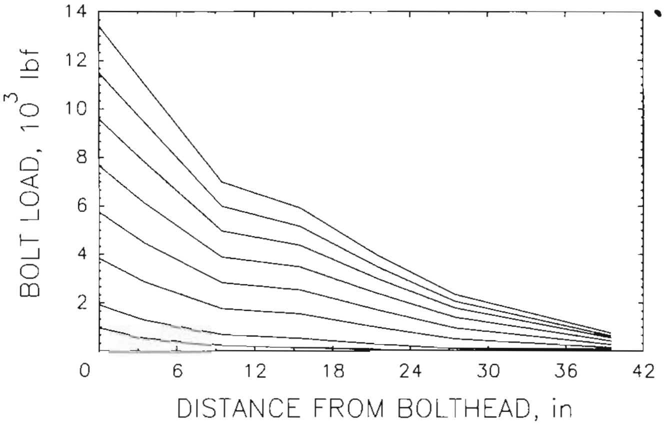

Figure 5.-Average results from mine 1.

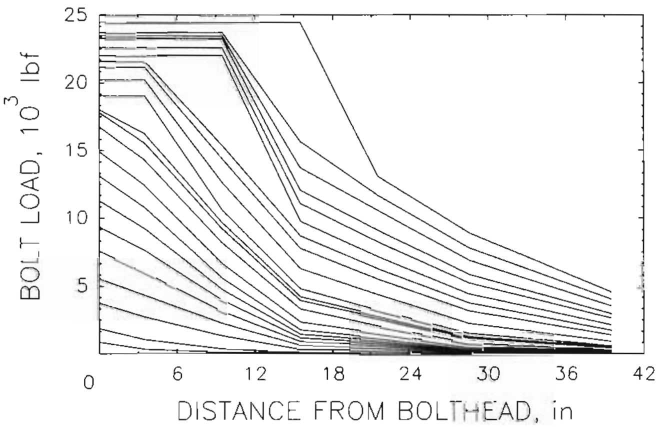

Figure 6.-Results from tests conducted past yield strength of steel bolt.

These variations in grout type and hole size had no statistically significant effect. An axisymmetric model was created to match stress distributions and bolt defections with those from the laboratory tests.

Figure 4*A* shows a comparison of load distributions along the lengths of 4-ft bolts using an applied load of 12,800 lbf for laboratory and field tests and the numerical model. Figure 4*B* compares the standard deviations derived from 50 bolts used in the laboratory work with 7 bolts from the field tests. These results show that bolts installed in shale required slightly longer lengths to transfer load between the bolt and the rock compared with bolts used in the laboratory tests. Standard deviations were larger for the field results. This is to be expected because of geological variations. Plots of the results of all field tests are included in the appendix.

The roof at mine 1 contained layers of weaker rock. Test results from five bolts installed and tested at this mine reflected the presence of these weaker layers as changes in the rate of load transfer. A weaker layer requires a longer anchorage length compared with that needed in stronger rock. The stiffness of the bolting system decreases in the weaker zones. Figure 5 shows a plot of data from one of the bolts tested at mine 1. Three bolts were installed and tested in mines 2, 3, and 4, a total of nine bolts.

POSTYIELDING TESTS

Comparatively small amounts of roof movement are required to cause a bolt to exceed the yield point of the steel. However, the steel used for grouted roof bolts is ductile and can sustain a large amount of deflection before it fails. After each bolt was tested in the elastic range, a test was conducted in which each bolt was loaded past the yield point of the steel. Typical test results are shown in figure 6, and the rest of the plots are included in the appendix.

Monitoring strain gauges until loads pass the yield point of the steel presents several problems. When a steel bolt yields, readings from the strain gauges are inaccurate past 5,000 microstrain. Another problem is caused as the bolthead stretches, sometimes more than 2 in. This deformation can cause the lead wires to the strain gauges to stretch and break. This stretch will change the resistance, which changes the relationship between electrical readings and load.

For these reasons, the load in a bolt is represented in the plots as the applied load after yielding has occurred at that station. Before the steel bolt yields, the grout will reach its peak shear strength and begin to fail. However, load is still transferred between the bolt and the rock by the residual shear strength of the grout. For this reason, the actual load in the bolt will be less than the applied load. The straight line represented in the yield zone is not a true representation of load distribution.

Readings were taken until the gauges no longer functioned properly. The depth of yield along the different bolt lengths varied significantly from 3.5 in (station 1) to 21.5 in (station 4). Because of the problems already mentioned, the depth of yielding could be farther along the bolt length, but that information was not practically obtainable.

CONCLUSIONS

The results from the axial elastic tests conducted on grouted bolts installed in shale compared well with the results from previous laboratory work and numerical modeling as detailed in reference 1. The average anchorage length for bolts installed in shale was slightly longer than for bolts installed in concrete blocks. The field results showed more variability.

Tests conducted past the yield point of the steel indicated that the yield zone will vary from bolt to bolt and will translate down the length of the bolt anywhere from 4 to 22 in. If there is sufficient length of bolt past the yield zone, then the load will transfer from the bolt to the rock, similar to the response shown in the elastic tests. This means that grouted bolts can still be an effective support past the yield point of the steel provided there is enough length to develop elastic decay.

Pull tests are routinely conducted on grouted bolts to evaluate anchorage capacity and installation quality. Results from this research show that the load applied during a standard pull test is dissipated into the rock within 24 in of the bolthead. However, anchorage at the end of the bolt, which is critical for proper support, is not being tested. Therefore, it is very difficult to evaluate properly the capacity of a grouted bolt by a standard pull test. Additional instruments, such as strain gauges, are required to provide a complete assessment of grouted bolts.

These results can be used as a guide when selecting grouted bolts for support of coal mine roofs. However, tests should be conducted for specific roof conditions to gain a thorough understanding of the material strengths of the immediate roof in specific mines.

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APPENDIX.–CALIBRATION PROCEDURES AND DATA REDUCTION

The calibration procedure used a linear statistical regression analysis to establish the relationship between applied load and voltage change. To ensure accuracy, data for the calibration of each bolt were taken from three loading cycles. The applied load was limited to the elastic range of the steel. The voltage change for each gauge was statistically correlated to the load to obtain a slope and an intercept. If variations larger than 0.5 pct were found, then the gauge was replaced. Calibrations for each gauge on each bolt were stored in a computer file and were used to reduce the experimental voltage readings to values for load automatically and to plot the results without manual data manipulation. Typically, the standard deviation of the predicted load value using a least squares linear fit was approximately ± 50 lbf. This meant that the strain gauges on the bolt measured the load to within 100 lbf. This procedure produced excellent test results with good repeatability.

DETAILS OF TEST EQUIPMENT

The data acquisition system consisted of a Hewlett-Packard (HP) 3421A data logger, a HP41CX calculator with a HP-IL interface, a HP82162A printer, and a HP82161A digital cassette drive. This system was used to provide 5 V of excitation to a Wheatstone bridge, measure the voltage changes, and record the readings on magnetic tape for later data retrieval and processing. All components of the system were battery powered for portability; however, this system was not permissible and had to be used in fresh air.

Test Data

Linear

The following plots (figs. A-1 through A-4) are the results of pull tests conducted in the elastic range of the bolts. Each test was an average of three runs. Load in a bolt was obtained by converting voltage readings to load by calibration factors obtained for each gauge. At mine 2, two bolts had insufficient grout to fill the hole completely, resulting in a partial column of grout. The test results from these two bolts showed similar load transfer characteristics from the start of the grout column (fig. A-2).

Postyield

The following plots (figs. A-5 through A-8) are the results of pull tests conducted past the yield point of the steel bar. Yield is represented by a straight line; however, this is not a true representation of the load in the bolt. When the applied load passed the yield point of the steel, stretching (and in some cases, failure) of the lead wires produced uncertain results.

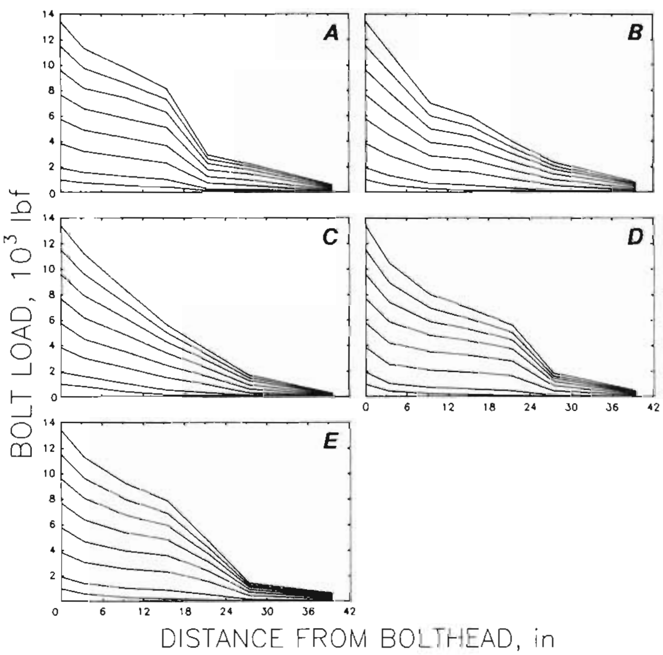

Figure A-1–Results from elastic test, mine 1. *A*, **Bolt 1;** *B*, **bolt 2;** *C*, **bolt 3;** *D*, **bolt 4;** *E*, **bolt 5.**

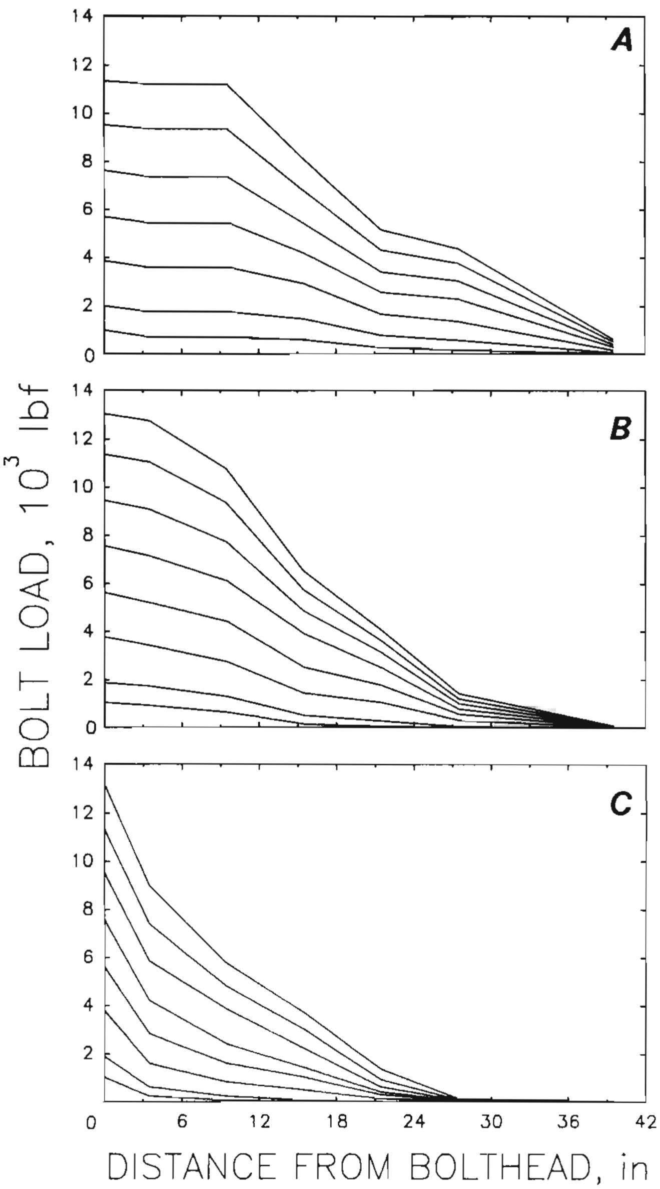

Figure A-2.–Results from elastic test, mine 2. *A*, **Bolt 1;** *B*, **bolt 2;** *C*, **bolt 3.**

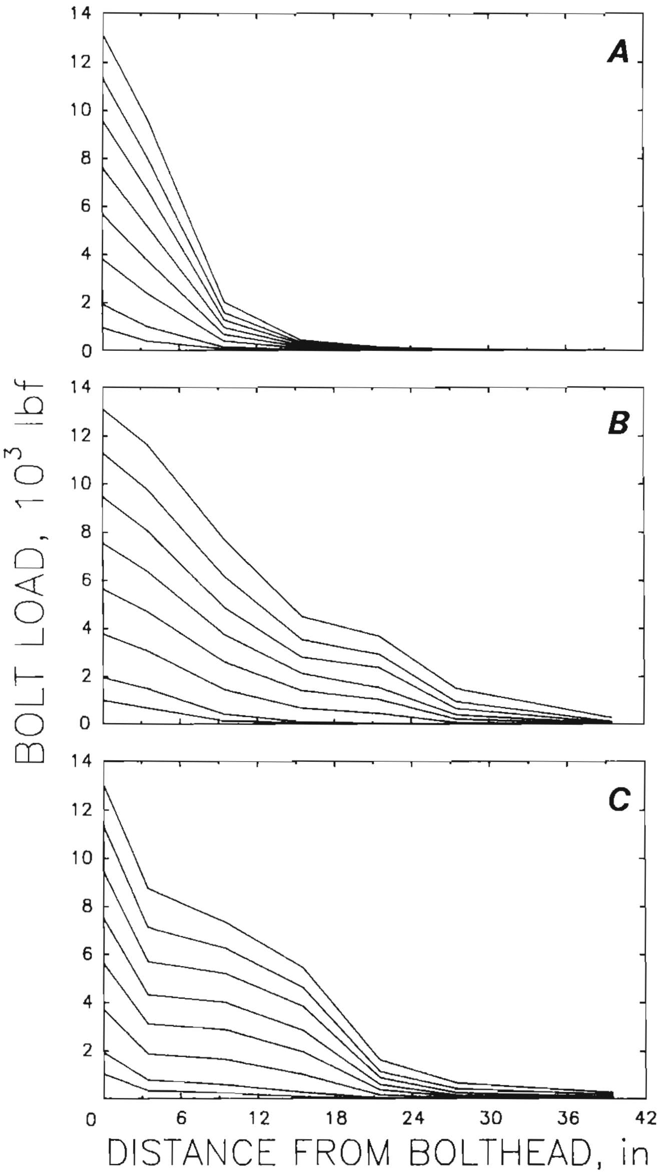

Figure A-3.–Results from elastic test, mine 3. *A*, Bolt 1; *B*, bolt 2; *C*, bolt 3.

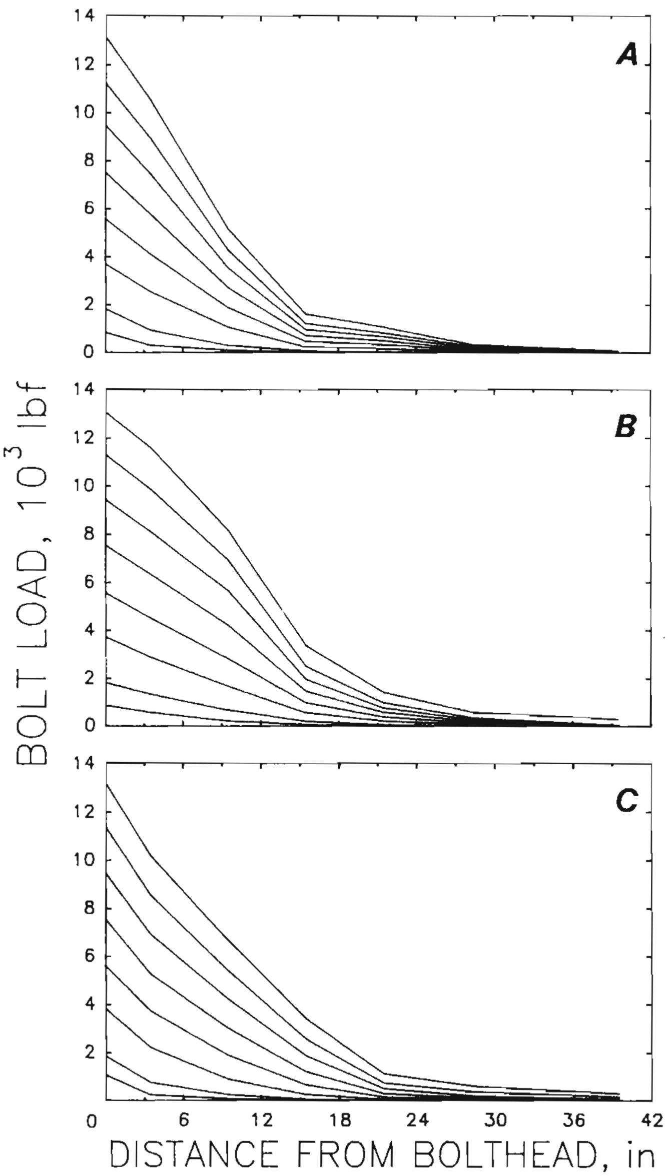

Figure A-4.–Results from elastic test, mine 4. *A*, Bolt 1; *B*, bolt 2; *C*, bolt 3.

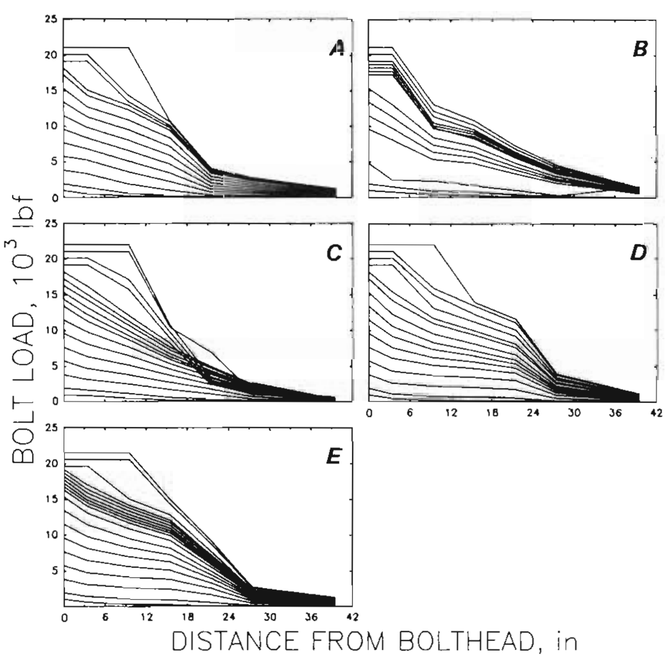

Figure A-5.–Results from plastic test, mine 1. *A*, **Bolt 1;** *B*, **bolt 2;** *C*, **bolt 3;** *D*, **bolt 4;** *E*, **bolt 5.**

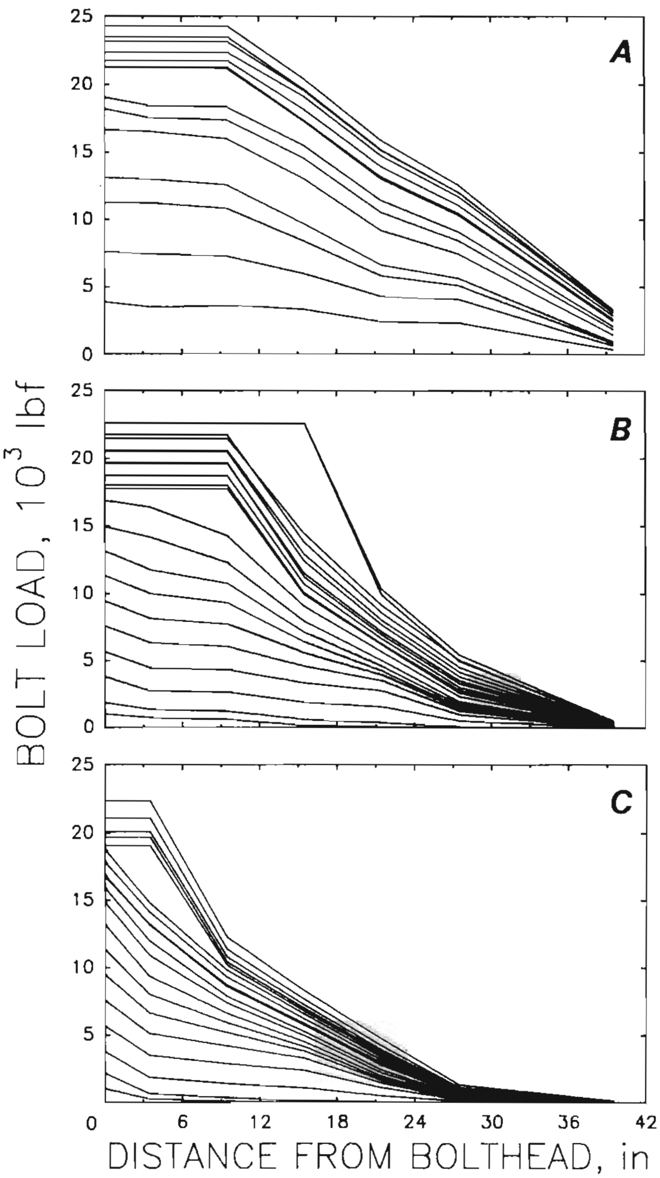

Figure A-6.–Results from plastic test, mine 2. *A*, **Bolt 1;** *B*, **bolt 2;** *C*, **bolt 3.**

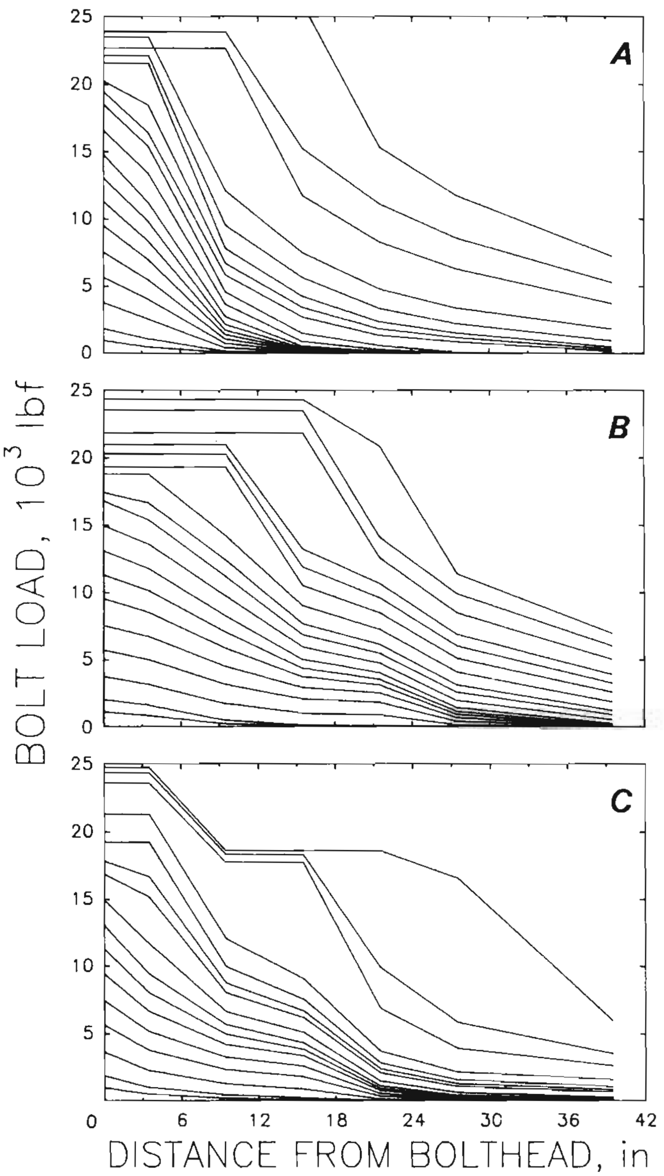

Figure A-7.–Results from plastic test, mine 3. *A*, **Bolt 1;** *B*, **bolt 2;** *C*, **bolt 3.**

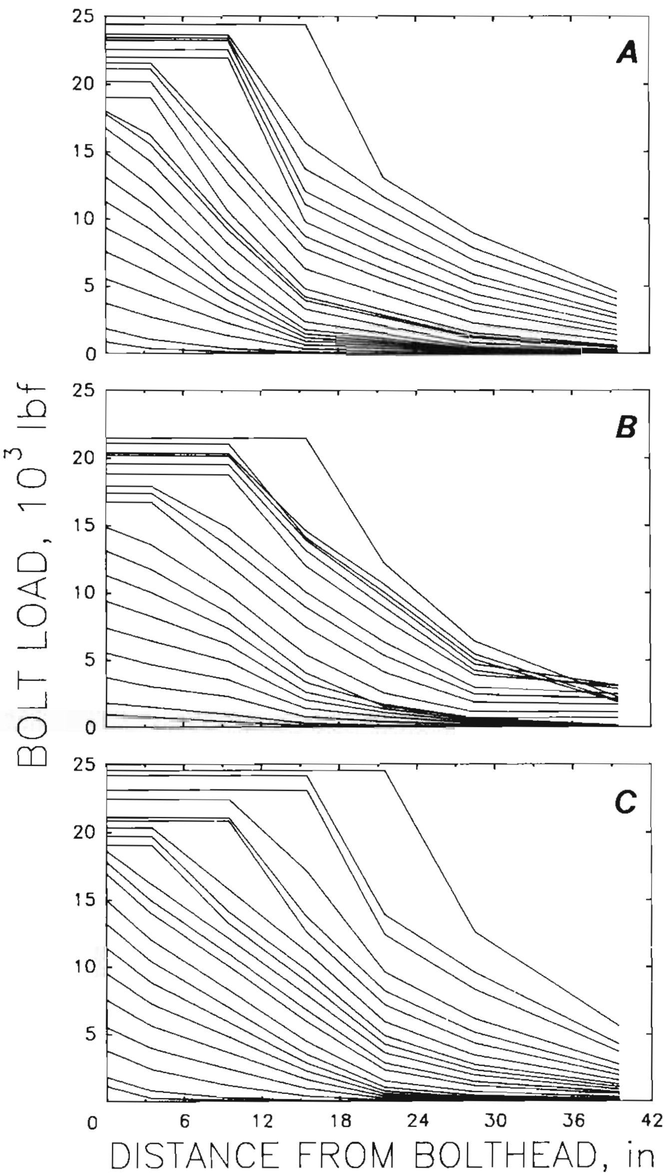

Figure A-8.–Results from plastic test, mine 4. *A*, **Bolt 1;** *B*, **bolt 2;** *C*, **bolt 3.**